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Pansier

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(54) **VOLTAGE GENERATOR**

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CPC ***H02M 3/158*** (2013.01); *H02M 2001/0058* (2013.01); *H02M 2007/4815* (2013.01); *Y02B 70/1425* (2013.01); *Y02B 70/1441* (2013.01); *Y02B 70/1491* (2013.01)

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USPC 363/15, 16, 17, 21.01–21.03, 363/21.06–21.08, 21.12, 21.15, 21.17, 363/21.18, 23, 34, 37; 323/234, 237, 265, 323/266, 271, 273, 275, 282–285
See application file for complete search history.

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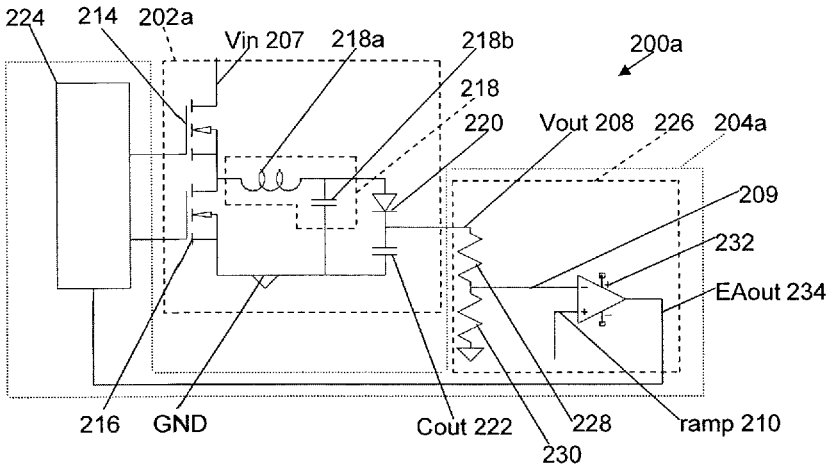
(57) **ABSTRACT**

The disclosure relates to a voltage generator for providing an output voltage in accordance with a received target signal, the voltage generator comprising: a resonant converter configured to receive an input voltage, the resonant converter comprising: a first switch; a second switch connected in series with the first switch between the input voltage and ground (GND); a resonant tank associated with the second switch; an output capacitor coupled to the resonant tank and configured to provide an output voltage; and a rectifier configured to allow charge to flow in a single direction between the resonant tank and the output capacitor; and a controller configured to receive the target signal and to set an operating parameter of the resonant converter in accordance with a difference between an output value which is related to the output voltage and the target signal.

17 Claims, 5 Drawing Sheets



(51) **Int. Cl.**
H02M 1/00 (2006.01)
H02M 7/48 (2007.01)

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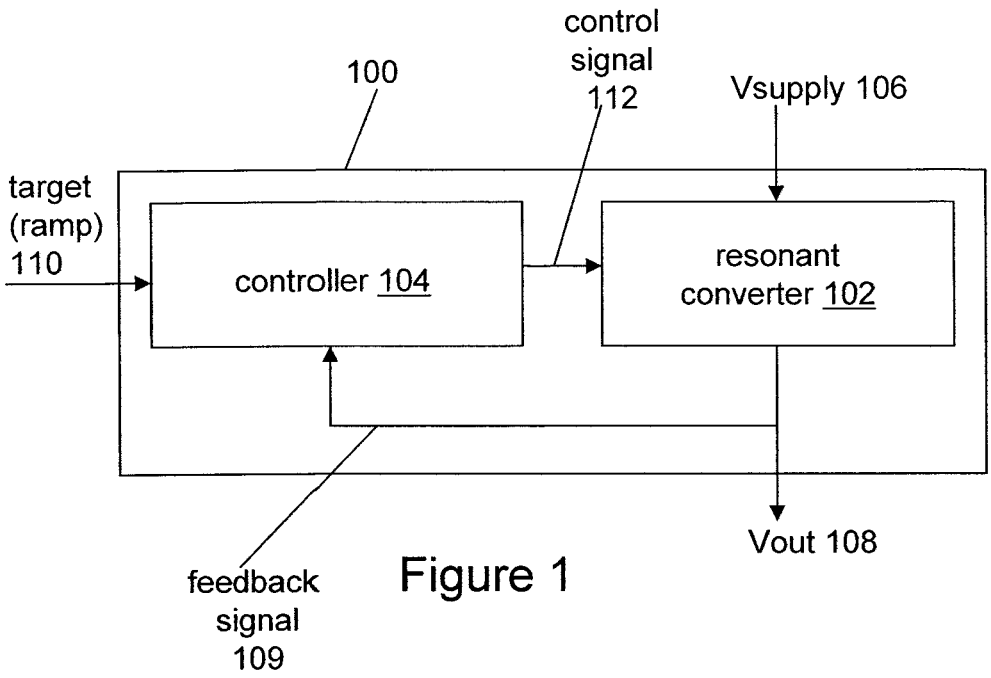

Figure 1

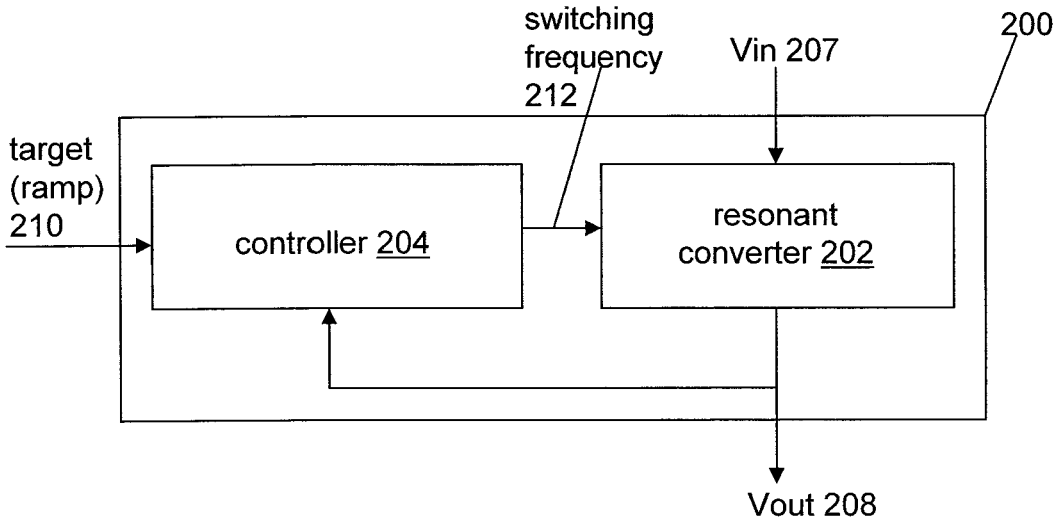

Figure 2a

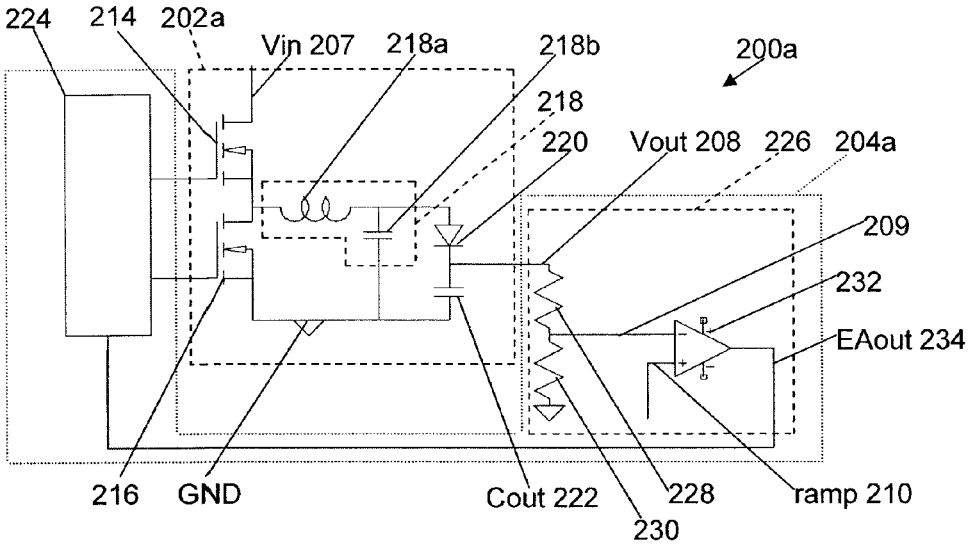

Figure 2b

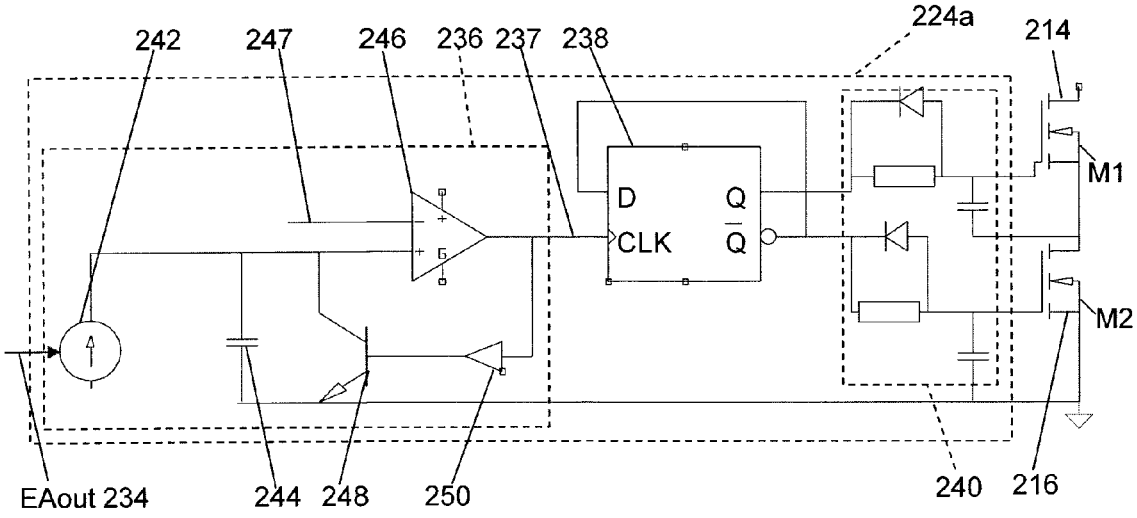

Figure 2c

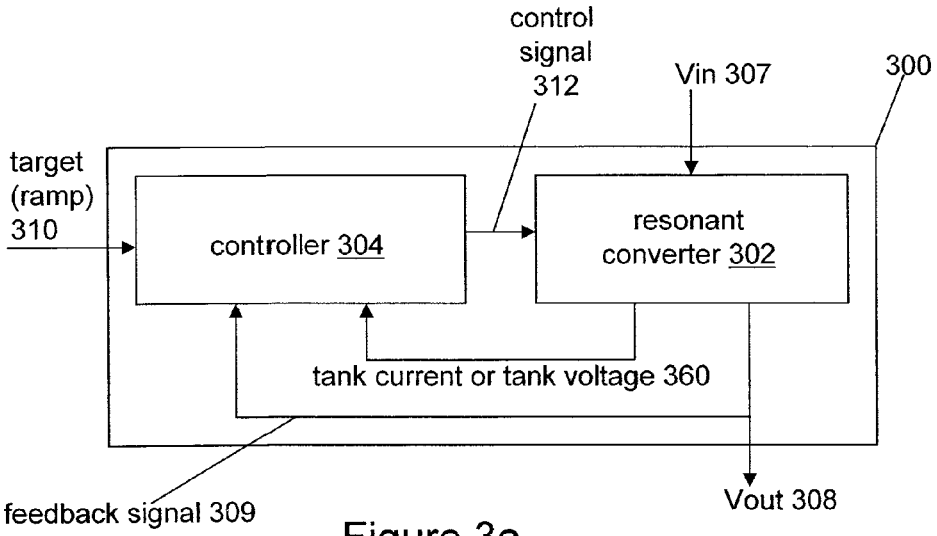

Figure 3a

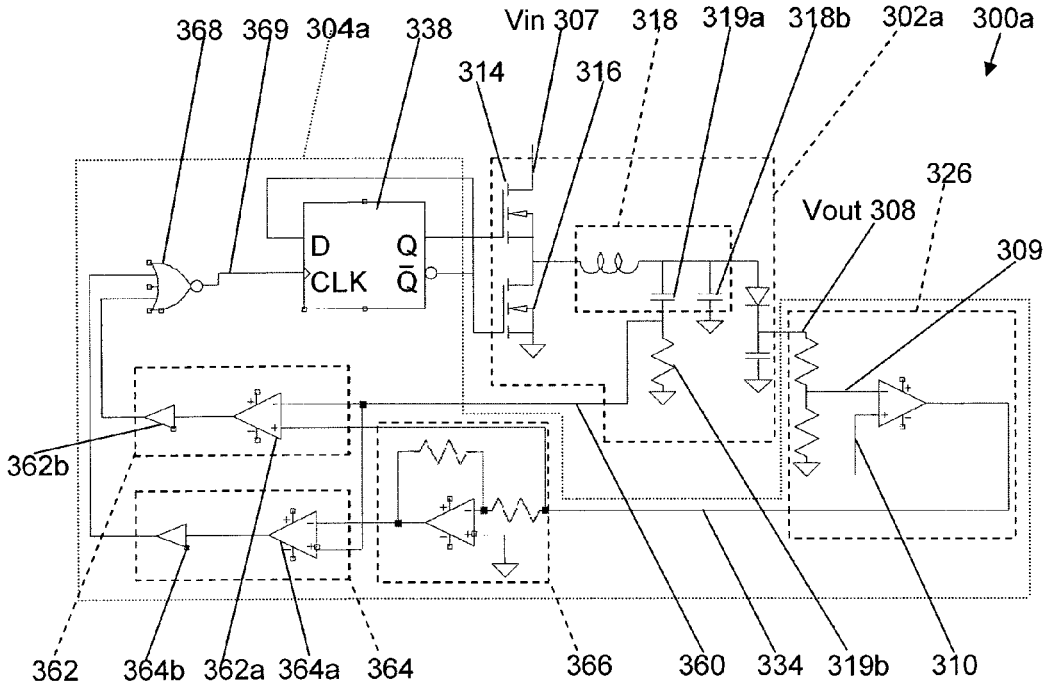

Figure 3b

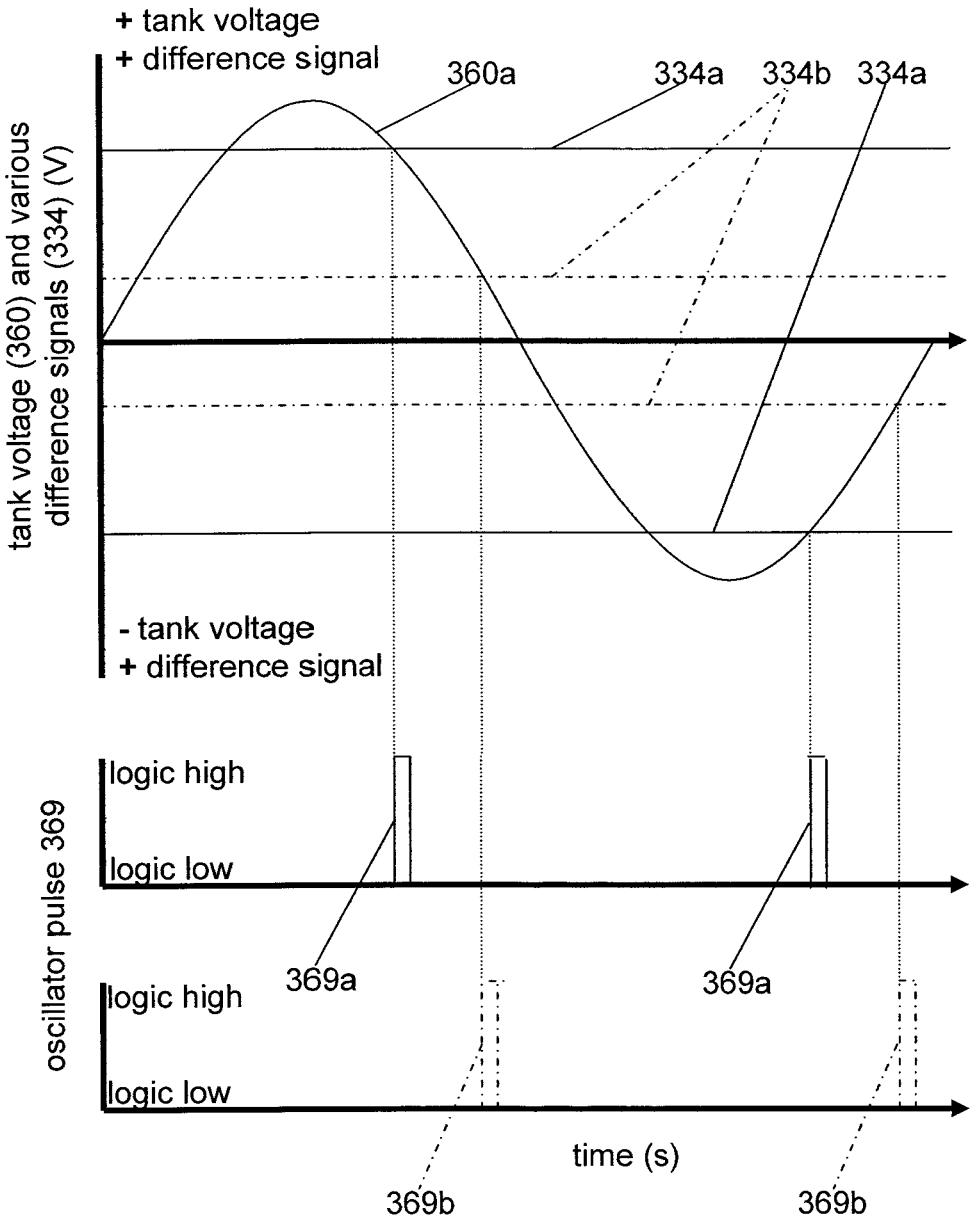
+ tank voltage
+ difference signal
360a
334a
334b
334a
tank voltage (360) and various difference signals (334) (V)
- tank voltage
+ difference signal
logic high
logic low
oscillator pulse 369
369a
369a
logic high
logic low
time (s)
369b
369b

Figure 3c

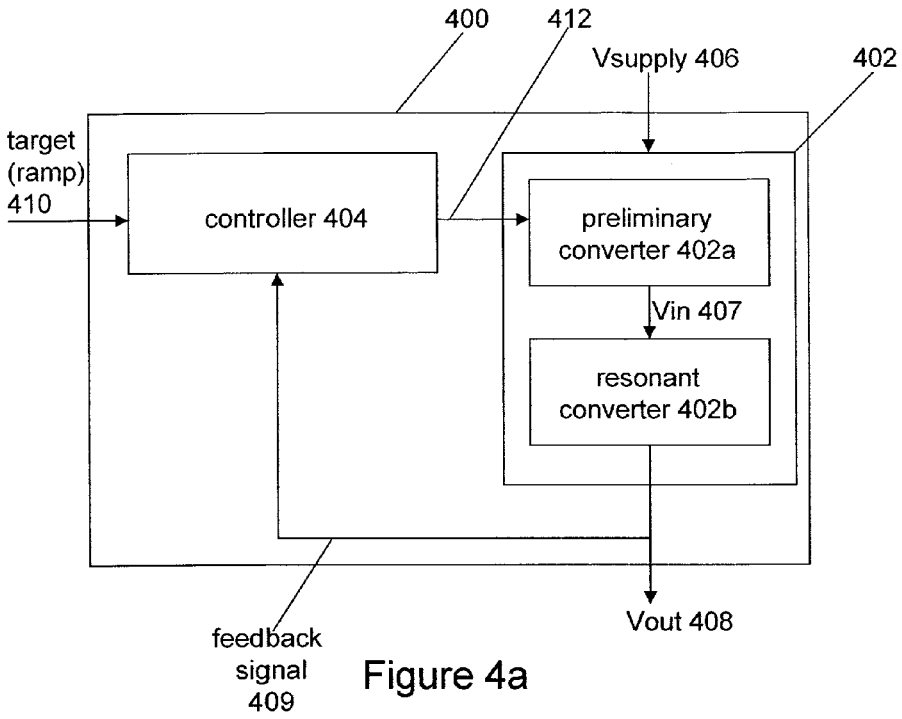

Figure 4a

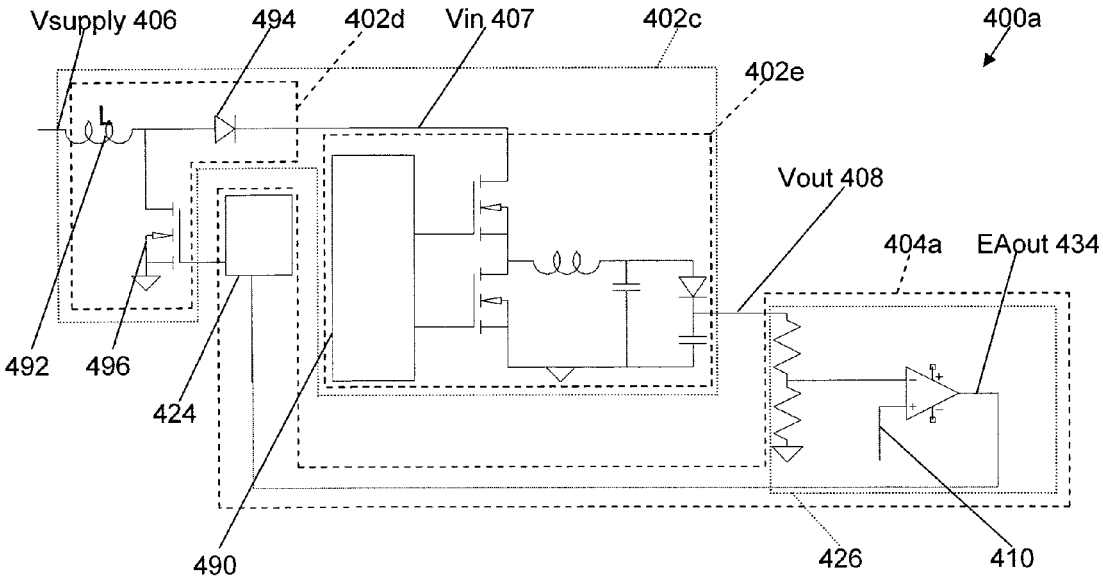

Figure 4b

VOLTAGE GENERATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the priority under 35 U.S.C. §119 of European patent application no. 13165828.8, filed on Apr. 29, 2013 the contents of which are incorporated by reference herein.

The present disclosure relates to voltage generators. Specifically, voltage generators for providing an output voltage in accordance with a received ramp, or target, signal.

Some applications require a high voltage (for example 3 kV) signal to be generated from a low voltage source, such as a Li-ion battery with a DC output of 2.7 V to 4.2 V. For example haptic feedback for mobile device applications can require a high voltage to be generated from a low voltage source. Such applications may also demand a specific rate of voltage ramping so that the generated high voltage relates to a desired level of haptic feedback.

A high voltage generator may be provided using a capacitive voltage multiplier. In such a voltage generator an input voltage for the multiplier is generated as a square wave voltage using a half bridge configuration. The rate of increase of the output voltage can be controlled by varying the switching frequency of the square wave input voltage of the half-bridge. A disadvantage of such voltage generators is that a high number of capacitive stages are required in order to provide a high conversion ratio (Vout/Vin). Providing such a voltage multiplier therefore involves a large number of components and occupies a correspondingly large PCB area. These disadvantages are particularly relevant to voltage generators that have a low input voltage.

The number of stages in a capacitive voltage multiplier can be reduced by introducing an intermediate converter, boosting the input voltage to a higher level. Such a modification reduces the number of multiplier stages but introduces an additional stage and also introduces additional losses, as the efficiency of the additional converter usually drops when the conversion ratio is very high (of the order of a thousand).

According to an embodiment of the present invention there is provided a voltage generator for providing an output voltage in accordance with a received target signal, the voltage generator comprising:

- a resonant converter configured to receive an input voltage, the resonant converter comprising:
  - a first switch;
  - a second switch connected in series with the first switch between the input voltage and ground;
  - a resonant tank associated with the second switch;
  - an output capacitor coupled to the resonant tank and configured to provide an output voltage; and
  - a rectifier configured to allow charge to flow in a single direction between the resonant tank and the output capacitor; and
- a controller configured to receive the target signal and to set an operating parameter of the resonant converter in accordance with a difference between an output value which is related to the output voltage and the received ramp signal.

The voltage generator uses a resonant topology and so may occupy less space and require fewer components than an equivalent capacitive voltage multiplier voltage generator. The controller can provide the functionality of conforming the output voltage to the desired voltage indicated by the target signal, which may be a ramp signal. The ramp signal may be provided by a haptic feedback application of a mobile computing device, for example.

The operating parameter may be a state of the first switch or the second switch. Setting an operating parameter may comprise toggling the states of the first switch and second switch. The output value may be the output voltage.

The controller may be configured to set the operating parameter in accordance with a comparison between a value related to a current in the resonant tank and a value related to the difference. The value related to the current in the resonant tank may be the current in the resonant tank. The controller may be configured to set the operating parameter when the value related to the resonant tank current is greater than the value related to the difference. The controller may be configured to operate the first and second switches at a specific point in time during a sinusoidal resonant tank current, such that the operating parameter is the phase of the sinusoidal resonant tank current at which the first and second switches are operated. The value related to the difference may be a modulus of the difference. Alternatively, the value related to the difference may be the difference.

The controller may be configured to operate the first and second switches according to a switching cycle that has a switching frequency. The operating parameter may be the switching frequency. The controller may be configured to restrict the operation of the first and second switches to switching frequencies that are greater than or equal to a resonant frequency of the resonant tank. The controller may be configured to increase the switching frequency if the output value is greater than the target signal. The controller may be configured to decrease the switching frequency if the output value is less than the target signal. The controller may be configured to decrease the switching frequency only if the switching frequency is greater than or equal to a resonant frequency of the resonant tank.

The operating parameter may be the input voltage of the resonant converter. The voltage generator may comprise a first stage converter configured to receive a supply voltage and to provide the input voltage of the resonant converter. The controller may comprise a switching controller configured to operate the first stage converter in accordance with the difference between the output value and the target signal. The first stage converter may be a boost converter. The boost converter may comprise a boost inductor with a first terminal and a second terminal. The first terminal may be connected to the supply voltage. The boost converter may comprise a boost rectifier. The boost rectifier may be connected to the second terminal of the boost inductor. The boost rectifier may be configured to provide the input voltage of the resonant converter. The boost converter may comprise a boost switch connected between the second terminal of the boost inductor and ground. The switching controller may be configured to operate the boost switch in accordance with the difference between the output value and the target signal.

According to a further aspect of the invention there is provided a mobile computing device comprising the voltage generator. The mobile computing device may be a mobile telephone, which may have a touch screen for which haptic feedback is required. The voltage generator may be well suited for providing an output voltage for driving such haptic feedback.

Embodiments of the present invention will now be described by way of example and with reference to the accompanying drawings in which:

FIG. **1** illustrates a block diagram of a voltage generator comprising a controller that is configured to set an operating

parameter of a resonant converter in accordance with a received target signal in order to provide a desired output voltage;

FIG. **2***a* illustrates a block diagram of a voltage generator similar to that of FIG. **1** in which the operating parameter is a switching frequency of the resonant converter;

FIG. **2***b* illustrates an example circuit diagram for a voltage generator in accordance with the block diagram of FIG. **2***a;*

FIG. **2***c* illustrates an example circuit diagram for a switching controller for use in the circuit of FIG. **2***b;*

FIG. **3***a* illustrates a block diagram of another voltage generator similar to FIG. **1** in which the operating parameter is a state of switches of the resonant converter and the controller further determines when to operate the switches in accordance with a current within the resonant converter;

FIG. **3***b* illustrates an example circuit diagram for a voltage generator in accordance with the block diagram of FIG. **3***a;*

FIG. **3***c* illustrates signals within the voltage generator of FIG. **3***b;*

FIG. **4***a* illustrates a block diagram of another voltage generator similar to FIG. **1** that comprises a preliminary converter, where the operating parameter is an input voltage of the resonant converter provided by the preliminary converter; and

FIG. **4***b* illustrates an example circuit diagram for a voltage generator in accordance with the block diagram of FIG. **4***a.*

FIG. **1** illustrates a block diagram of a voltage generator **100** that is configured to receive a supply voltage (Vsupply) **106** and provide an output voltage (Vout) **108** in accordance with a received target, or ramp, signal **110**. The voltage generator **100** can be used to generate a high voltage in accordance with a desired ramp rate as specified by the target signal **110**. A specific example of where such a voltage generator **100** may be used is in the provision of haptic feedback in mobile device applications. Such examples may benefit from a physically small circuit that can provide a high voltage waveform of a desired shape from a low voltage supply.

The voltage generator **100** comprises a resonant converter **102** and a controller **104**. The controller **104** is configured to receive the target signal **110** and a feedback signal **109** from the resonant converter **102**. The feedback signal is representative of an output value of the resonant converter, which in this example is related to the output voltage (Vout) **108**. The controller **104** can then send a control signal **112** to set an operating parameter of the resonant converter **102** in accordance with a difference between the feedback signal **109** and the target signal **110**.

Various preferred and optional features of the voltage generator are described further with reference to FIGS. **2** to **4**. The voltage generators described herein may be provided using off-the-shelf components. Alternatively, components may be custom made in order to reduce a PCB footprint of the voltage generator.

FIGS. **2***a* and **2***b* illustrate a voltage generator **200**, **200***a* similar to that of FIG. **1** in which the operating parameter that is set by the controller is a switching frequency **212** of the resonant converter **202**.

FIG. **2***a* illustrates a block diagram of the voltage generator **200**. Any mismatch between the switching frequency represented by the control signal **212** applied by the controller **204** and the resonant frequency of the resonant converter **204** leads to a lower rate of increase in the output voltage (Vout) **208**. This is because the resonant converter **202** operates sub-optimally (in terms of maximising output voltage) if the switching frequency does not match the resonant frequency. The controller **204** uses this principle to ensure that the output voltage (Vout) **208** of the resonant converter **202** corresponds to a desired voltage indicated by the target (ramp) signal **210**.

The operation of the voltage generator may be better understood by reference to FIGS. **2***b* and **2***c*, which illustrate circuit diagrams for an example voltage generator **200***a*. The voltage generator **200***a* comprises a resonant converter **202***a* and a controller **204***a*. The resonant converter **202***a* of FIG. **2***b* comprises a first switch **214**, a second switch **216**, a resonant tank **218**, a rectifier **220** and an output capacitor **222**.

Isolation between an input voltage **207** and an output voltage **208** of the resonant converter **202***a* may not be required in applications that generate a high voltage from a battery. It is therefore not essential for the resonant converter **202***a* to comprise a transformer. As such, space can be saved, as can the component cost of a transformer.

The first switch **214** is connected in series with the second switch **216** between the input voltage (Vin) **207** and ground (GND). In this example, the input voltage **207** can be considered to be a supply voltage. The first and second switches **214**, **216** can be provided as transistor switches, such as the MOSFETs illustrated in FIG. **2***b* in which case the drain-source conduction channels of the respective FET switches **214**, **216** are provided in series.

The resonant tank **218** may contain any arrangement of components that provide impedance. In this example, the resonant tank **218** comprises a tank inductor **218***a* and a tank capacitor **218***b* provided in series with each other. The resonant tank **218** is associated with the second switch **216**. In this example the resonant tank **218** is provided in parallel with the second switch **216**.

A square wave potential can be applied to the resonant tank **218** at the node between the first and second switches **214**, **216** by alternately toggling the states of the first and second switches **214**, **216**. If the toggling of the switches **214**, **216** is performed at an appropriate frequency (given the impendence of the tank **218**) then each switching action can add an amount of energy to the resonant tank **218**. For a fixed switching frequency, a fixed amount of energy is added to the resonant tank **218** per switching cycle. An alternating current (AC) waveform is generated in the resonant tank **218** at a connecting node of the resonant inductor **218***a* and the resonant capacitor **218***b*. The RMS voltage of the AC waveform is proportional to the amount of energy stored in the resonant tank **218**.

The output capacitor **222** has a first plate and a second plate. The second plate of the output capacitor **222** is connected to ground (GND).

The rectifier **220** couples the first plate of the output capacitor **222** to the resonant tank **218**. In this example, the output capacitor **222** is coupled in parallel with the tank capacitor **218***b*. The rectifier **220** can be provided by a diode and is configured to allow charge to flow in a single direction between the resonant tank **218** and the output capacitor **222** such that energy can be passed to the output from the resonant tank during half of the switching cycle, but not flow back from the output to the resonant tank during the other half of the switching cycle. An output voltage (Vout) **208** can be taken between the first plate of the output capacitor **222** and ground (GND).

The rectifier allows charge to flow when the instantaneous value of the AC wave in the resonant tank **218** is greater than the (DC) output voltage (Vout) **208** stored by the capacitor

222. The flow of charge through the rectifier **220** results in an increase in the output voltage (Vout) **208**. The rate of rise is dependent on the characteristic impedance of the resonant tank **218**. The component values of the resonant tank **218** can therefore be optimised to reduce the amount of controlling adjustment required for a given application.

The controller **204** is configured to receive the target signal **210** and to set a switching frequency of the first and second switches **214**, **216** of the resonant converter **202** in accordance with a difference between a voltage related to the output voltage (Vout) **208** and the target signal **210**. The controller **204***a* in this example comprises a switch controller **224** and error amplifier circuitry **226**.

The error amplifier circuitry **226** comprises a potential divider and an error amplifier **232**. The potential divider has a first resistor **228** and a second resistor **230** that are coupled in series between the first plate of the output capacitor **222** and ground such that the output voltage (Vout) **208** is dropped across the two resistors **228**, **230**. The potential divider provides a divided voltage (with respect to ground) at a junction between the first resistor **228** and the second resistor **230**. The divided voltage is an example of a feedback signal **209** representative of an output value that relates to the output voltage (Vout) **208**. The feedback signal **209** is supplied to an inverting input of the error amplifier **232**.

The error amplifier **232** also receives the target signal (ramp) **210** at its non-inverting input and provides a difference signal (EAout) **234** at its output. An amplitude of the difference signal (EAout) **234** relates to the difference between the feedback signal **209** and the target signal (ramp) **210**. When the output voltage (Vout) **208** is lower than required, the difference signal (EAout) **234** will be positive. When the output voltage (Vout) **208** is greater than required, the difference signal (EAout) **234** will be negative.

The switch controller **224** is configured to receive the difference signal (EAout) **234** and set the switching frequency of the first and second switches **214**, **216** in accordance with the difference signal (EAout) **234**.

The switch controller **224** may be configured to operate the resonant converter **202***a* only at switching frequencies that are greater than or equal to the resonant frequency of the resonant tank **218**. Use of switching frequencies below the resonant frequency can cause inefficiencies in operation of the resonant converter **202** as it can generate capacitive switching, which lowers the efficiency of the system due to switching losses and can damage FET switches **214**, **216**. Known techniques for preventing capacitive switching are implemented in the TEA1713 and TEA1716 controllers and described in WO 2009/037613.

The switching controller **224** may be configured to decrease the switching frequency if the feedback signal **209** is less than the target signal **210** (the difference signal **234** is positive), as long as the switching frequency is greater than or equal to the resonant frequency of the resonant tank **218**. The output voltage (Vout) **208** will be at its maximum when the switching frequency is equal to the resonant frequency. The value for the resonant frequency used by the switching controller **224** may be a measured value, or may be a worst case (highest possible) value given the tolerances of the components in the resonant tank **218**. Typical tolerances are 20% for an inductor and 10% for a high voltage capacitor.

The switching controller **224** may be further configured to increase the switching frequency if the feedback signal **209** is greater than the target signal **210** (the difference signal **234** is negative). Increasing the switching frequency away from the resonant frequency results in a reduced output voltage (Vout) **208**. Alternatively, the amplifier circuitry **226** may be restricted to providing positive (or zero) difference signals (EAout) **234** at its output.

An example switch controller **224***a* is illustrated in FIG. **2***d*.

The switching controller **224***a* comprises an oscillator unit **236** that provides a square wave oscillator signal **237** with a switching frequency in accordance with the difference signal (EAout) **234**. The oscillator signal **237** is provided to a divide-by-two counter **238** that toggles the states of the first and second switches **214**, **216**. Buffer circuitry **240** is provided to ensure that the first and second switches **214**, **216** cannot be closed at the same time, which would result in a short circuit of the supply voltage.

The oscillator **236** comprises a variable current source **242** that provides a current at a level that is related to the difference signal (EAout) **234**. A direct current from the current source **242** is provided to a first plate of a timing capacitor **244**. The second plate of the timing capacitor **244** is coupled to ground. A potential (or timing voltage) across the timing capacitor **244** increases as the timing capacitor **244** charges up. An oscillator comparator **246** has a non-inverting input coupled to the first plate of the timing capacitor **244** and an inverting input coupled to an oscillator reference voltage **247** (which may be fixed). An output of the oscillator comparator **246** goes high when the timing voltage of the timing capacitor **244** reaches that of the oscillator reference voltage **247**. The output of the oscillator comparator **246** is provided to a base of a shorting transistor **248** via a delay buffer **250**. The shorting transistor **248** has a conduction channel that couples the first plate of the timing capacitor **244** to the second plate of the timing capacitor **244**. Therefore, once the timing capacitor **244** has charged up to the threshold set by the oscillator reference voltage **247**, it will be discharged through the shorting transistor **248** after a delay set by the delay buffer **250**. A pulse is therefore provided at the output of the oscillator comparator **246** at a frequency dependent on the rate of charging of the timing capacitor **244** as set by the current level provided by the variable current source **247**.

The current source **242** may be provided by a bipolar transistor, which provides a current level equal to the base current minus a multiple of the difference signal **234** (Ibase−k*EAout, where k is a constant). The rate of charging of the timing capacitor **244** (and therefore oscillator/switching frequency) will therefore increase as the negative difference signal **234** decreases. That is, the switching frequency will increase when the feedback signal **209** is greater than (or equal to) the target signal **234**. Increasing the oscillatory frequency takes the resonant converter **202***a* further away from the resonant frequency and so reduces the output voltage Vout **208**, so allowing the output voltage (Vout) **208** to tend towards the target signal **210**.

The value of the base current and/or the oscillator reference voltage **247** may be chosen such that the lowest oscillator frequency is twice the resonant frequency, taking into account the tolerance of the components in the resonant tank **218**. For example, if the expected resonant frequency is 2 MHz, then when the tolerance of the tank inductor **218***a* is 20% and the tolerance of the tank capacitor **218***b* is 10%, than the worst case (highest possible) resonant frequency may be 2.36 MHz. It will be appreciated that different settings will be appropriate depending on the voltage range of the error amplifier **232** (for example, if the error amplifier **232** can only provide a zero or positive output).

The divide-by-two counter **238** may be implemented using a D-type flip-flop, as shown in FIG. **2***c*. The flip-flop

has a clock input (CLK), an output (Q), an inverted output ($\overline{Q}$), and a data terminal (D). The clock input (CLK) of the flip-flop receives the output of the oscillator comparator **246** of the oscillator **236**. The output (Q) of the counter **238** is provided to the first switch **214** via a path of the buffer circuitry **240**. The inverted output ($\overline{Q}$) is provided to the data terminal (D) and a gate of the second switch **216** via a path of the buffer circuitry **240**. Each path of the buffer circuitry **240** comprises a resistor in parallel with a reverse-biased diode (with regard to the flip-flop output) and a capacitor that couples the path to a source of the respective FET switch **214**, **216** of that path. In this way, a RCD network is used to implement a delay that is provided during switch commutation to ensure that the first and second switches **214**, **216** are not simultaneously closed. It will be appreciated that various other forms of the optional buffer circuiting **240** may be provided.

The switching controller **224***a* may control the resonant converter **202***a* such that the output voltage (Vout) **208** follows (lags) the desired output voltage as indicated by the target signal **210**. The maximum output voltage (Vout) **208** depends on the Q-factor of the resonant tank **218***a* and the input voltage **207** of the resonant converter **202***a*.

FIGS. **3***a* and **3***b* illustrate a voltage generator **300**, **300***a* similar to that of FIG. **1** in which the operating parameter is a state of the switches in the resonant converter. FIG. **3***a* illustrates a block diagram of the voltage generator **300**.

The voltage generator **300** comprises a resonant converter **302** and a controller **304**. The controller **304** is configured to receive a target signal **310** and to provide a control signal **312** to set an operating parameter of the resonant converter **302** in accordance with a resonant tank feedback signal **360** representative of a current level in a resonant tank of the resonant converter **302**; a feedback signal **309** that is similar to the corresponding feedback signal of FIG. **2***a*; and the target signal **310**.

The controller **304** is configured to operate the first and second switches **314**, **316** in order to define a switching cycle that has a specific phase relative to the sinusoidal current in the resonant tank of the resonant converter **302**. The controller **304** uses the phase of the switching cycle as the operating parameter. That is, the controller **304** is configured to modify the phase of the switching frequency in accordance with the difference between the target signal **310** and the feedback signal **309** which is related to the output voltage **308**.

The optimum instance for commutating the resonant converter **302** in order to maximise the output voltage is the instant that the tank current in the resonant converter is zero. This corresponds to switching the resonant converter at the resonant frequency. Altering the phase of commutation so that switching does not coincide with when the tank voltage **360** is zero means that less energy is imparted to the resonant tank by each switching cycle. This causes a reduction in the output voltage (Vout) **308**.

In this example, the controller **304** may not need to use an adapted resonant switching frequency to account for the tolerances of the resonant tank. This is because the tolerances of the resonating components will be automatically taken into account by such methodology as the resonant converter **302** is controlled in accordance with measured values of current in the resonant tank as opposed to theoretical values.

The controller **304** may be used after an initial switching cycle of the half bridge has been completed as it requires measurements from a previous switching cycle to function correctly. An oscillator, such as that described with reference to FIG. **2** for example, may be used to generate the initial switching cycle, or cycles, in order to set up resonance in the resonant tank **318**.

An implementation of the voltage generator **300** of FIG. **3***a* will be described with reference to FIG. **3***b*, which illustrates a circuit diagram of an example voltage generator **300***a*. The voltage generator **300***a* comprises a resonant converter **302***a* and a controller **304***a*. The controller **304***a* has error amplifying circuitry **326** and a switching controller (the remainder of the controller **304***a*).

The resonant converter **302***a* is similar to that illustrated in FIG. **2***b*, except for modifications to the resonant tank **318**, which comprises a sampling capacitor **319***a* and a sampling resistor **319***b* coupled in series. The series arrangement of the sampling capacitor **319***a* and the sampling resistor **319***b* are provided in parallel with the tank capacitor **318***b*. The sampling capacitor **319***a* may have a capacitance that is substantially lower, such as 100, 1000 or 10,000 times lower, than the capacitance of the tank capacitor **318***b*. The voltage dropped across the sampling resistor **319***b* is proportional to the current in the sampling capacitor **319***a* and is referred to as a tank voltage **360**. The tank voltage **360** is therefore indicative of a current in the resonant tank **318**.

The tank voltage **360** enables the controller **304***a* to determine the instantaneous phase in the sinusoidal resonant tank current. The controller **304***a* can modify the timing of commutation of the first and second switches **314**, **316** of the resonant converter **302***a* so that switching occurs at a specific point/phase in the sinusoidal resonant current. It will be appreciated that, in general, a switch commutation at one phase position of a resonant cycle will add a different amount of energy to the resonant tank **318** than application of a switch commutation at a different phase position of the resonant cycle. As such, the phase timing of switch commutation can be used to vary the output voltage (Vout) **308** of the resonant converter **302***a*.

The error amplifier circuitry **326** provides a difference signal **334** in accordance with the target signal **310** and the feedback signal **309** which is related to the output voltage **308**. The error amplifier circuitry **326** is substantially as described with reference to FIG. **2***b*, but may be configured to limit, or clamp, the possible value of the difference signal **334** to be equal to, or just below, the maximum possible tank voltage that may be taken across the sampling resistor **319***b*. This modification is desirable to ensure that switching is not halted in the case when the highest possible difference signal **334** increases above the tank voltage. Such clamping is well known by those skilled in the art of the designing of integrated circuits. In this example, the error amplifier circuitry **326** may be limited to providing a difference signal (EAout) **310** that cannot have a negative value.

The controller **304***a* is configured to compare the tank voltage **360** with the difference signal **334**. The controller **304***a* may optionally be configured to compare the tank voltage **360** with the modulus of the difference signal **334**. In the example of FIG. **3***b* such a comparison is achieved by employing a first comparison path **362** and a second comparison path **364**. An analogue inverter **366** is provided between the error amplifying circuitry **326** and the second comparison path **364** so that the second comparison path **364** receives an inverted difference signal.

Each comparison path **362**, **364** comprises a comparator **362***a*, **364***a* that compares the tank voltage **360** with the difference signal **334** and a buffer **362***b*, **364***b* that buffers the output of the comparator **362***a*, **364***a*. The comparator **362***a* of the first comparison path **362** receives the tank voltage **360** at an inverting input and the difference signal **334** at a

non-inverting input. The comparator **364***a* of the second comparison path **364** receives the tank voltage **360** at a non-inverting input and the difference signal **334** at an inverting input. The buffers **362***b*, **364***b* receive the Boolean output from the respective comparators **362***a*, **364***a* and produce a pulse on each rising edge between a low and high signal. Output of the logic paths may be better understood with reference to FIG. **3***c*, which is discussed in further detail below.

Logic **368** performs an 'OR' operation on the signals received from the first and second comparison paths **362**, **364** and provides an oscillator pulse **369** to a divide-by-two counter **338**.

The divide-by-two counter **338** may be implemented using a D-type flip-flop having a clock input (CLK), an output (Q), an inverted output ($\overline{Q}$), and a data terminal (D). The clock input (CLK) of the flip-flop receives the output of the OR gate. The output (Q) of the counter **338** may be provided to the first switch **314** of the resonant converter **302***a* via a path of buffer circuitry, such as the buffer circuitry in FIG. **2***c*. The inverted output ($\overline{Q}$) may be provided to the data terminal (D) and a gate of the second switch **316** of the resonant converter **302***a* via a path of the buffer circuitry.

FIG. **3***c* illustrates graphically a tank voltage **360***a*, a high difference signal **334***a* and a low difference signal **334***b* that may be present in the circuit of FIG. **3***b*. The tank voltage **360***a* is a sinusoidal signal that has positive and negative values. The high and low difference signals **334***a*, **334***b* are representative of difference signals that may be provided by the error amplifier circuitry **326** depending upon the difference between the feedback signal **309** and the target signal **310**. The high and low difference signals **334***a*, **334***b* are positive values in all instances as the error amplifier circuitry **326** is limited to providing positive difference signals **334** in this example. The difference signals **334***a*, **334***b* are illustrated mirrored across the horizontal axis, to illustrate both: i) the difference signal **334** that is provided to the first comparison path **362** of FIG. **3***b*; and ii) the inverted difference signal that is provided to the second comparison path **364** of FIG. **3***b*.

FIG. **3***c* also illustrates oscillator pulses **369***a*, **369***b* that are produced by the switching controller and relate to respectively the corresponding positive low difference signals **334***a* and high difference signals **334***b* intersecting the tank voltage **360***a*. Corresponding oscillator pulses **369***c*, **369***d* are produced for the associated negative difference signals **334***a*, **334***b*. It will be appreciated that the high and low difference signals **334***a*, **334***b* are illustrative of different circuit states and are not provided simultaneously. The corresponding oscillator pulses **369***a*, **369***b* are presented on different time axes to illustrate this.

The configuration of the comparison paths **362**, **364** of the controller **304***a* are such that the switches **314**, **316** are commutated when the modulus of the tank voltage **360** falls below the difference signal **334**. For example, the comparator **362***a* of the first comparison path **362** provides a high output signal when the tank voltage **360** falls below the difference signal **334**. The corresponding buffer **362***b* produces a pulse on the transition from a low to high comparator **362***a* output.

FIG. **3***c* demonstrates that the oscillator pulse **369** (which results in commutation of the first and second switches **314**, **316**) occurs at a different phase position of the sinusoidal tank voltage waveform **360***a* depending upon the amplitude of the difference signal **334**. That is, there is a phase difference between the oscillator pulses **369***a* associated with high difference signal **334***a* and the oscillator pulses **369***b* associated with lower difference signals **334***b*.

The oscillator pulses **369***b* associated with the low difference signal **334***b* are provided near to the zero-crossing of the tank voltage **360***a*, whereas the oscillator pulses **369***a* associated with the high difference signal **334***a* are provided further away from the zero-crossing of the tank voltage waveform **360***a*, nearer the maximum value of the tank voltage waveform **360***a*. When commutation of the switches **314**, **316** takes place before the current in the resonant tank **318** has dropped to zero, less energy is put into the resonant tank **318** per full switching cycle, and so less charge is transferred to the output capacitor per unit time. The net effect of the difference in the phase of commutation on the switching frequency is small; the main influence of the phase of commutation is that the average tank voltage changes and therefore so does the output voltage. The amplitude of the tank voltage waveform **360** tends to increase when the difference signal **334** is low and tends to decrease when the difference signal **334** is high.

If the output voltage **308** is greater than the desired output voltage (as indicated by the target signal **310**), commutation is performed such that the instants in time at which the switches are operated are set such that they do not coincide with a zero-crossing of the tank voltage waveform **360***a* so that the output voltage **308** is reduced. In this way, the ramp-up speed of the output voltage (Vout) **308** can be controlled. A consequence of this type of control algorithm is that the output voltage **308** may tend to lead the target signal **310**.

In the case where the difference signal **334** equals the peak of the tank voltage waveform **360***a*, the average rate of energy addition to the resonant tank **318** is zero. During half the on-time of the positive half wave of the tank voltage waveform **360***a*, the input voltage to the resonant tank is Vin; the other half of that time it is zero. The average voltage is therefore Vin/2, and the associated increase of energy equals that of a regular switching but with Vin/2. However, during the negative part of the tank voltage waveform **360***a*, the input voltage is also present, but in this part of the sine wave the additional voltage counteracts the current. That is, the energy that is put into the resonant tank **318** during the positive half wave is removed during the negative half wave and so there is no net increase in the energy in the resonant tank or the output voltage.

The level of performance of the voltage generators described above with reference to FIGS. **2** and **3** can be dependent on the required conversion ratio (output voltage/input voltage). At a low input voltage (such as 1 to 3 V, for example), a limited amount of energy can be put into the resonant tank in each switching cycle, thereby limiting the possible maximum output voltage. In addition, the resonant currents in the resonant tank can become quite high in some implementations. The demands of handling high currents can require the resonant tank to have a high quality factor and can also mean that higher accuracy in switch commutation timing and voltage sensing may be required.

FIG. **4***a* illustrates a block diagram of a voltage generator **400** in which the converter **402** comprises a first stage converter **402***a* in addition to a resonant converter **402***b*. The resonant converter **402***b* can be a standard resonant converter or any resonant converter described herein. It will be appreciated that a standard resonant converter can be controlled such that it has a switching frequency that corresponds with the resonant frequency of the converter, thereby maximising the output voltage for a given input voltage to the resonant converter.

The first stage converter **402***a* receives a supply voltage **406** and provides the input voltage to the resonant converter **402***b*. The voltage generator **400** can address the above problems by providing an input voltage **407** to the resonant converter **402** that is higher than the supply voltage **406**, which therefore reduces the conversion ratio required of the resonant converter **402***b*. In such an example, the input voltage of resonant converter is the operating parameter of the converter that can be set.

The resonant converter **402***b* is configured to receive the input voltage (Vin) **407** and provide an output voltage (Vout) **408**. As the amount of energy that can be added to a resonant tank of the resonant converter **402***b* in a switching cycle depends on the input voltage **407** of the resonant converter **402***b*, the output voltage (Vout) of the converter can therefore be controlled by setting the input voltage **407** of the resonant converter **402***b*.

The voltage generator **400** comprises a controller **404** that is configured to receive a target signal **410** and provide a control signal **412** to set a parameter, in this example a switching frequency, of the first stage converter **402***a* in accordance with a feedback signal **409** which is related to the output voltage (Vout) **408** and the target signal **410**. The switching frequency of the first stage converter **402***a* affects the voltage (Vin) **407** (which is the input voltage to the resonant converter **402***b*) that is generated by the first stage converter **402***a* from the supply voltage **406** (Vsupply). In effect, the controller **404** sets an input voltage **407** of the resonant converter **402***b* as an operating parameter in accordance with a difference between the feedback signal **409** and the target signal **410**.

An implementation of the voltage generator **400** of FIG. **4***a* will be described with reference to FIG. **4***b*, which illustrates a circuit diagram of an example voltage generator **400***a*. The voltage generator **400***a* has a converter **402***c* comprising a first stage converter **402***d* and a resonant converter **402***e*. In this example, the first stage converter **402***d* is a boost converter that is configured to receive the supply voltage **406** and to provide an input voltage **407** to the resonant converter **402***e*. It will be appreciated that other converters could be used.

The resonant converter **402***e* is similar to that of FIG. **2***b* and common components between these figures will not be discussed in further detail here. The resonant converter **402***e* further comprises a resonant switching controller **490** that may be configured to operate the resonant converter **402***e* at its resonant frequency, which is the most efficient mode in which to operate the resonant converter **402***e*.

The first stage converter **402***d* comprises a boost inductor **492**, a boost rectifier **494** and a boost switch **496**. The boost inductor **492** has first terminal and a second terminal. The first terminal is arranged to receive the supply voltage **406**. The boost rectifier **494** is connected to the second terminal of the boost inductor **492** and is configured to provide the input voltage **407** of the resonant converter **402***e*. The boost switch **496** is connected between the second terminal of the boost inductor **492** and ground. The boost switch **496** can be provided by a FET, in which case a conduction channel of the FET is connected between the second terminal of the boost inductor **492** and ground.

The voltage generator **400***a* also comprises a controller **404***a*. The controller **404***a* comprises a switch controller **424** and error amplifier circuitry **426**. The error amplifier circuitry **426** is similar to that of FIG. **2***b* or **3***b* and provides a difference signal (EAout) **434** to the switch controller **424** in accordance with a difference between the output voltage **408** and the target signal **410**. The switch controller **424** is configured to set a switching frequency or state of the boost switch **496** in accordance with the difference signal (EAout) **434**. The output of the boost converter **402***d* is related to the switching frequency of the boost switch **496** as is known in the art. In this way, the output voltage can be made to conform to the desired voltage indicated by the target signal **410**.

It will be appreciated that features described in relation to one example may be provided in addition to the features illustrated in any other example, unless an intention to the contrary is apparent.

Terms such as "steep", "rapid", "large", "small", "high", "low", etc. used herein can be considered as greater than a threshold value, less than a threshold value, or between two threshold values depending upon the context.

Any components that are described herein as being "coupled" or "connected" could be directly or indirectly coupled or connected. That is, one or more components could be located between two components that are said to be coupled or connected whilst still enabling the required functionality to be achieved.

The invention claimed is:

1. A voltage generator for providing an output voltage in accordance with a received target signal, the voltage generator comprising:

a resonant converter configured to receive an input voltage, the resonant converter comprising:

a first switch;

a second switch connected in series with the first switch between the input voltage and ground (GND);

a resonant tank associated with the second switch;

an output capacitor coupled to the resonant tank and configured to provide an output voltage; and

a diode connected directly to the resonant tank and configured to allow charge to flow in a single direction from the resonant tank to the output capacitor;

an output located directly between the diode and the output capacitor to output the output voltage; and

a controller configured to receive the target signal and to set an operating parameter of the resonant converter in accordance with a difference between an output value which is related to the output voltage at the output and the target signal;

wherein the first switch and the second switch are transistor switches in which the drain-source conduction channels of the respective transistor switches are in series; and

wherein the first switch and the second switch are connected in a half-bridge configuration with the resonant tank connected between the first switch and the second switch.

2. The voltage generator of claim **1** wherein the operating parameter is a state of the first switch or the second switch.

3. The voltage generator of claim **2** wherein setting an operating parameter comprises toggling the states of the first switch and second switch.

4. The voltage generator of claim **1** wherein the controller is configured to set the operating parameter in accordance with a comparison between a value related to a current in the resonant tank and a value related to the difference.

5. The voltage generator of claim **4** wherein the controller is configured to set the operating parameter when the value related to the resonant tank current is greater than the value related to the difference.

6. The voltage generator of claim **4** wherein the controller is configured to operate the first and second switches at a specific point in time during a sinusoidal resonant tank

current, such that the operating parameter is the phase of the sinusoidal resonant tank current at which the first and second switches are operated.

7. The voltage generator of claim **4** wherein the value related to the difference is a modulus of the difference.

8. The voltage generator of claim **7** wherein the controller is configured to restrict the operation of the first and second switches to switching frequencies that are greater than or equal to a resonant frequency of the resonant tank.

9. The voltage generator of claim **8** wherein the controller is configured:

to increase the switching frequency if the output value is greater than the target signal; and

to decrease the switching frequency if the output value is less than the target signal, as long as the switching frequency is greater than or equal to a resonant frequency of the resonant tank.

10. The voltage generator of claim **1** wherein the controller is configured to operate the first and second switches according to a switching cycle that has a switching frequency, wherein the operating parameter is the switching frequency.

11. The voltage generator of claim **1** wherein the operating parameter is the input voltage of the resonant converter.

12. The voltage generator of claim **11** comprising a first stage converter configured to receive a supply voltage and to provide the input voltage of the resonant converter.

13. The voltage generator of claim **12** wherein the controller comprises a switching controller configured to operate the first stage converter in accordance with the difference between the output value and the target signal.

14. The voltage generator of claim **13** wherein the first stage converter is a boost converter comprising:

a boost inductor with a first terminal and a second terminal, the first terminal connected to the supply voltage;

a boost rectifier connected to the second terminal of the boost inductor and configured to provide the input voltage of the resonant converter; and

a boost switch connected between the second terminal of the boost inductor and ground,

wherein the switching controller is configured to operate the boost switch in accordance with the difference between the output value and the target signal.

15. A mobile computing device comprising the voltage generator of claim **1**.

16. The voltage generator of claim **1** in which the direct connection between the resonant tank and the diode is free of a transformer.

17. The voltage generator of claim **1** wherein the first switch and the second switch are MOSFETs in which the drain-source conduction channels of the respective MOSFETs are in series.

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